PBMR Fuel Design and Qualification

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September 22, 2005

Presentation Topics

- Pre-application focus issues
- Fuel performance envelope
- Compliance with the performance envelope
- Planned PBMR tests
- Manufacturing process and controls
- Previous RAIs
- Pre-application milestones and documentation

Issue Definition

- **Background**
  - Integrity of PBMR fuel particles is a critical characteristic of PBMR.
  - German TRISO fuel design selected as the reference design
    - *Proven experience 1967 - 1989 at German AVR and THTR facilities*
  - German manufacturing process adopted for PBMR fuel plant
  - New tests expected to confirm current performance envelope
  - Computer code and monitoring limits being developed to demonstrate that fuel behavior will be within performance envelope

- **Issue**
  - Demonstrate adequacy of the fuel qualification program by confirming:
    - *Fuel performance envelope*
    - *Methods for showing conformance with that envelope*
    - *Methods for showing equivalence in German vs. PBMR fuel manufacturing*

Focus Issues

- *Extent* of PBMR tests required to confirm and complete the German fuel performance envelope
- *Means* of showing compliance with the performance envelope during reactor operation
- *Extent* of documentation on equivalence of PBMR and German fuel manufacturing

Issue Focus – First Meeting Slide

- *Extent* of tests with regard to confirming the performance envelope
- *Means* of showing compliance with the performance envelope over time
- *Extent* of documentation on equivalence of PBMR and German fuel manufacturing

PBMR

Outcome Objectives

- Identification of scope of the fuel qualification test program
- Agreement on methods and monitoring to confirm that fuel design complies with the performance envelope
- Understanding of the scope of documentation

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German Test Envelope Summary

Parameter Ranges for German Irradiation Tests				
Phase	Temperature (^{o}C)	Burn-up (%FIMA)	Fast Neutron Dose E>0.1 MeV (x 10^{25} m^{-2})	Duration (EFPD)
1	880/1320	7.2/15.3	0.1/8.0	232/682
2	903/1140	7.81/10.88	3.2/5.9	585/834

Phases 1 and 2 performed at the High Flux Reactor (Petten)

Phase 1: 211,936 coated particles

Phase 2: 145,320 coated particles

Total: 357,256 coated particles simulating normal operation irradiation

PBMR Normal Operation Envelope

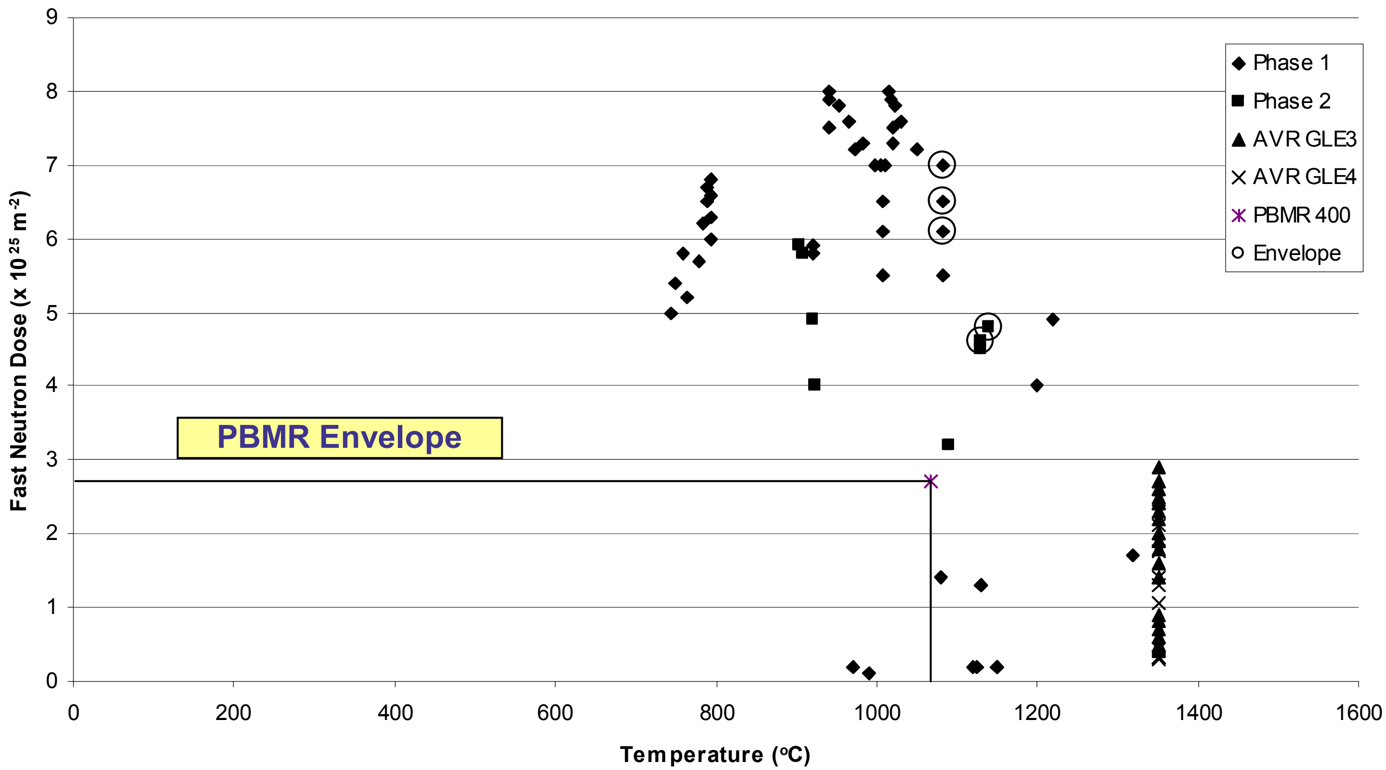
- Temperature 1068^{o}C
- Burn-up 10.1 %FIMA (maximum)
- Fast Neutron Dose 2.72 x 10^{21} cm^{-2}

- Data may change slightly as analyses are finalized

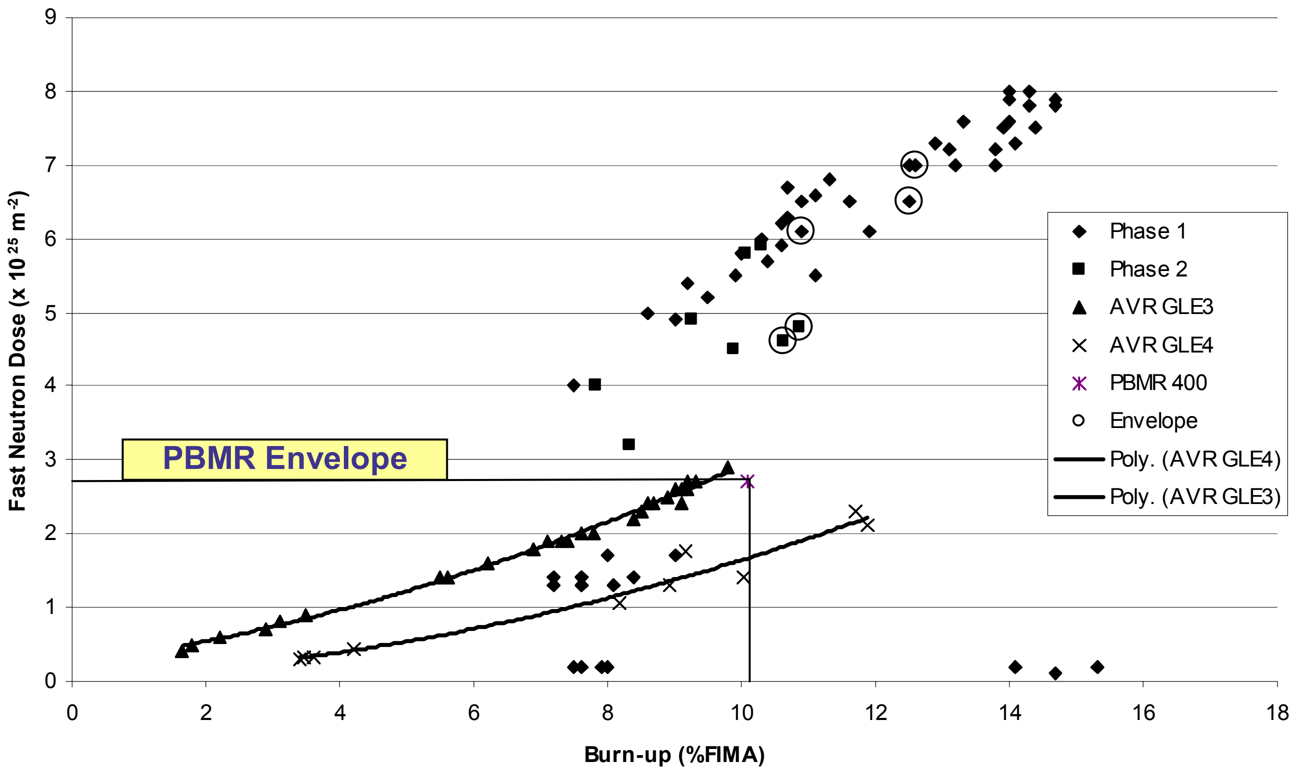
PBMR Operating Envelope

- **The following graphs compare the PBMR operating limits to the German irradiation test data, two parameters at a time:**
  - Fast neutron dose as a function of maximum fuel sphere temperature
  - Fast neutron dose as a function of burn-up
  - Burn-up as a function of maximum fuel sphere temperature

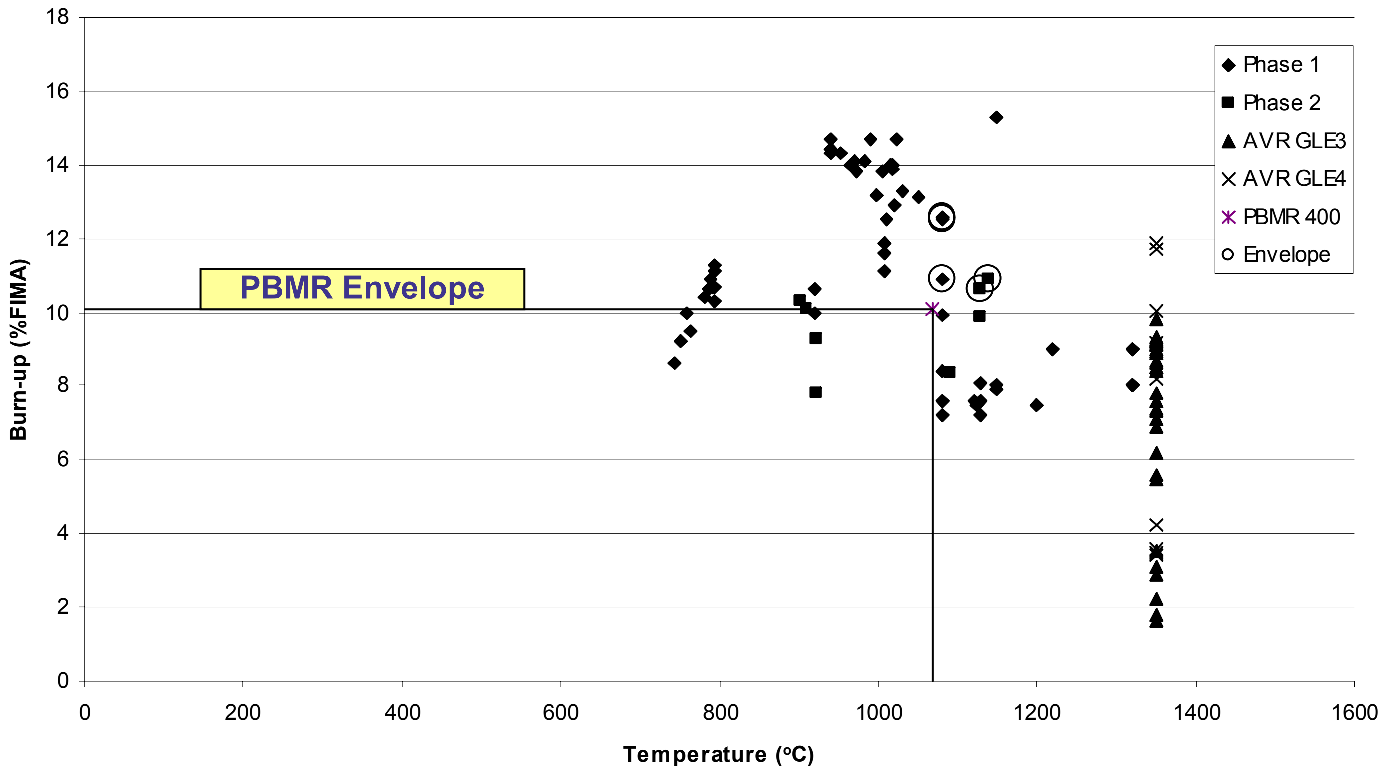
PBMR Operating Envelope



PBMR Operating Envelope…



PBMR Operating Envelope…



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Operating Limit Margins

- **Selection of operating limits includes margin to account for**
  - Defective coated particles created during manufacture
  - Coated particle failures during normal irradiation
  - Coated particle failures during DBA heat-up

- **The following slides address each of these categories**
  - A graph of failure fraction vs. temperature can be constructed from results of statistical analyses
    - *Address both "expected" and "design" failure fractions*

Particle Failures During Manufacture

- **Analysis of 528,200 fresh-fuel coated particles showed an expected failure fraction of 1×10^{-5} due to manufacturing**
  - The 95% upper limit failure fraction was 3×10^{-5}
  - The fuel specification has a "lot limit" of 6×10^{-5}
- **The "lot-limit" selected as a conservative value for design calculations**

Particle Failures During Normal Operation

- **From the 357,256 particles irradiated during the Phase 1 and Phase 2 tests, the 95% upper limit failure fraction was 8.4×10^{-6}**
  - 4.2×10^{-6} on a core average basis

Particle Failures During DBA Heat-up

- Fuel sphere heat-up during postulated accidents may result in additional coated particle failures

German Heat-up Tests

Parameter Ranges for German Irradiation Tests				
Phase	**Temperature (^{o}C)**	**Burn-up (%FIMA)**	**Fast Neutron Dose E>0.1 MeV (x 10^{25} m^{-2})**	**Duration (EFPD)**
1	880/1320	7.2/15.3	0.1/8.0	232/682
2	903/1140	7.81/10.88	3.2/5.9	585/834
AVR	<1400	1.6/11.88	0.31/2.9	-

Irradiated Particles Subsequently Heated to Simulate DBA Heat-up:

Phase 1 / Phase 2: 93,417 particles

AVR: 295,200 particles

Total: 388,617 particles

Heat-up Test Summary

- **Failure fraction from heat-up tests to 1600°C**
  - Mean: 2.4×10^{-5}
  - 95% upper limit: 4.7×10^{-5}

- **Failure fraction from heat-up tests to 1800°C**
  - Mean: 1.6×10^{-4}
  - 95% upper limit: 2.4×10^{-4}

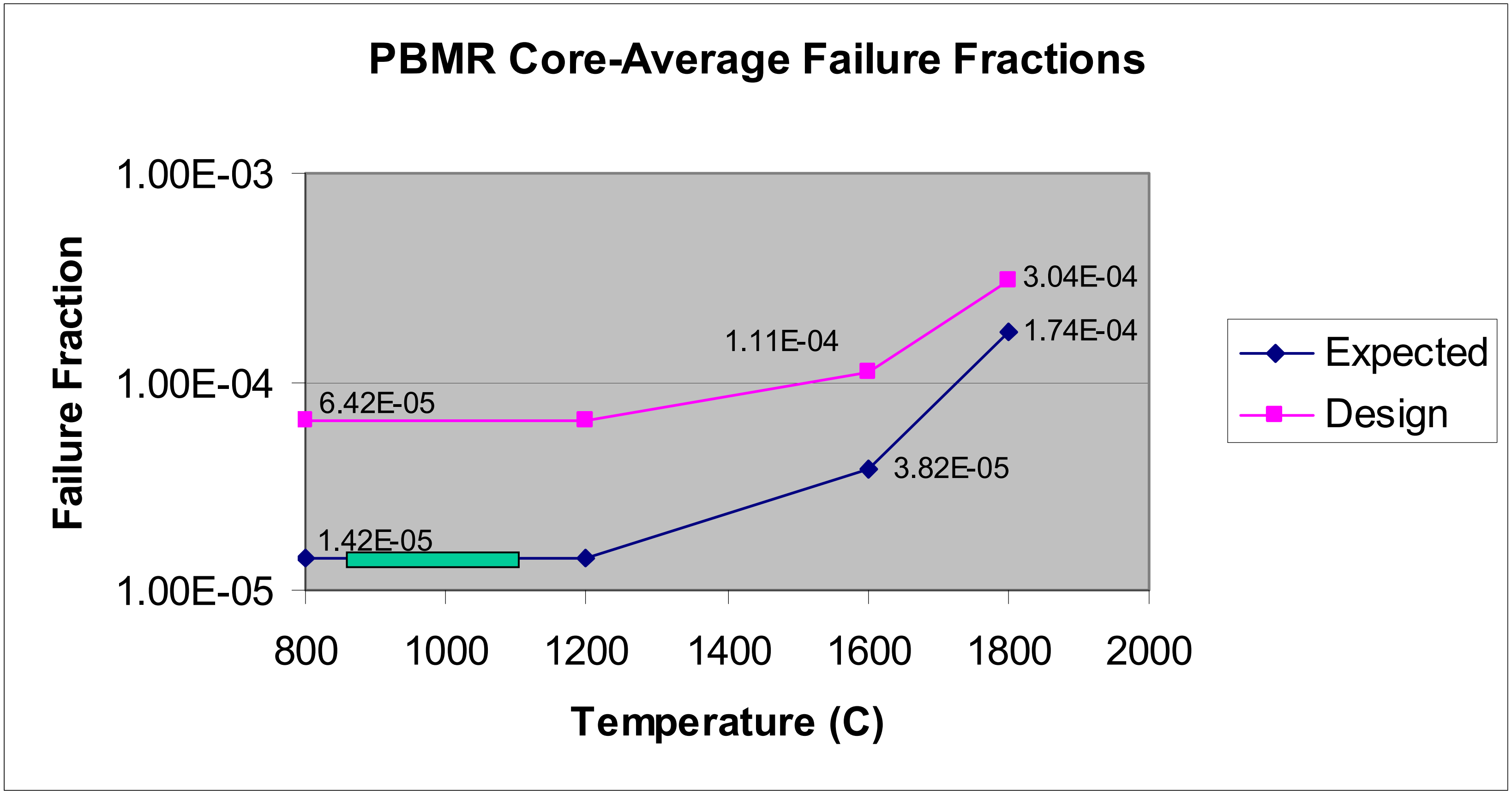
Failure Fraction vs. Temperature

- **A graph of failure fraction vs. temperature can be constructed from results of statistical analyses**
  - Use mean value as “expected” value
  - Use 95% upper limit value as “design” value

Failure Fraction Summary

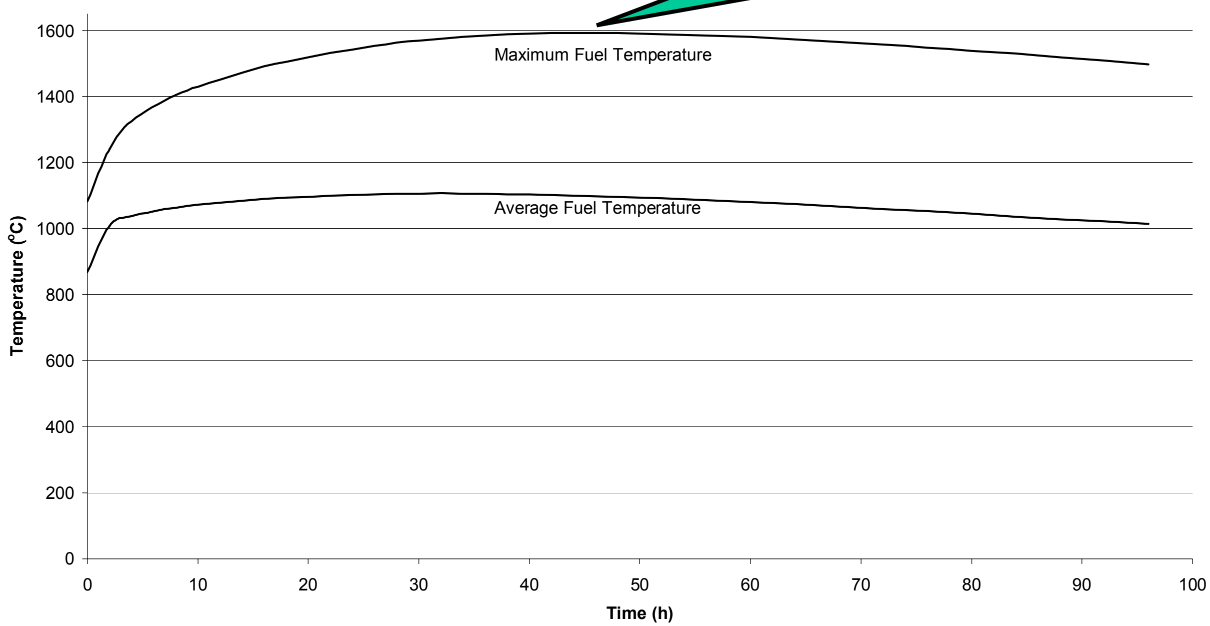
	Fresh Fuel	Irradiated Fuel	Fuel Heated to 1600ºC	Fuel Heated to 1800ºC
Expected	1.42x10-5	1.42x10-5	3.82x10-5	1.74x10-4
Design	6.42x10-5	6.42x10-5	1.11x10-4	3.04x10-4

PBMR Core Average Failure Fractions



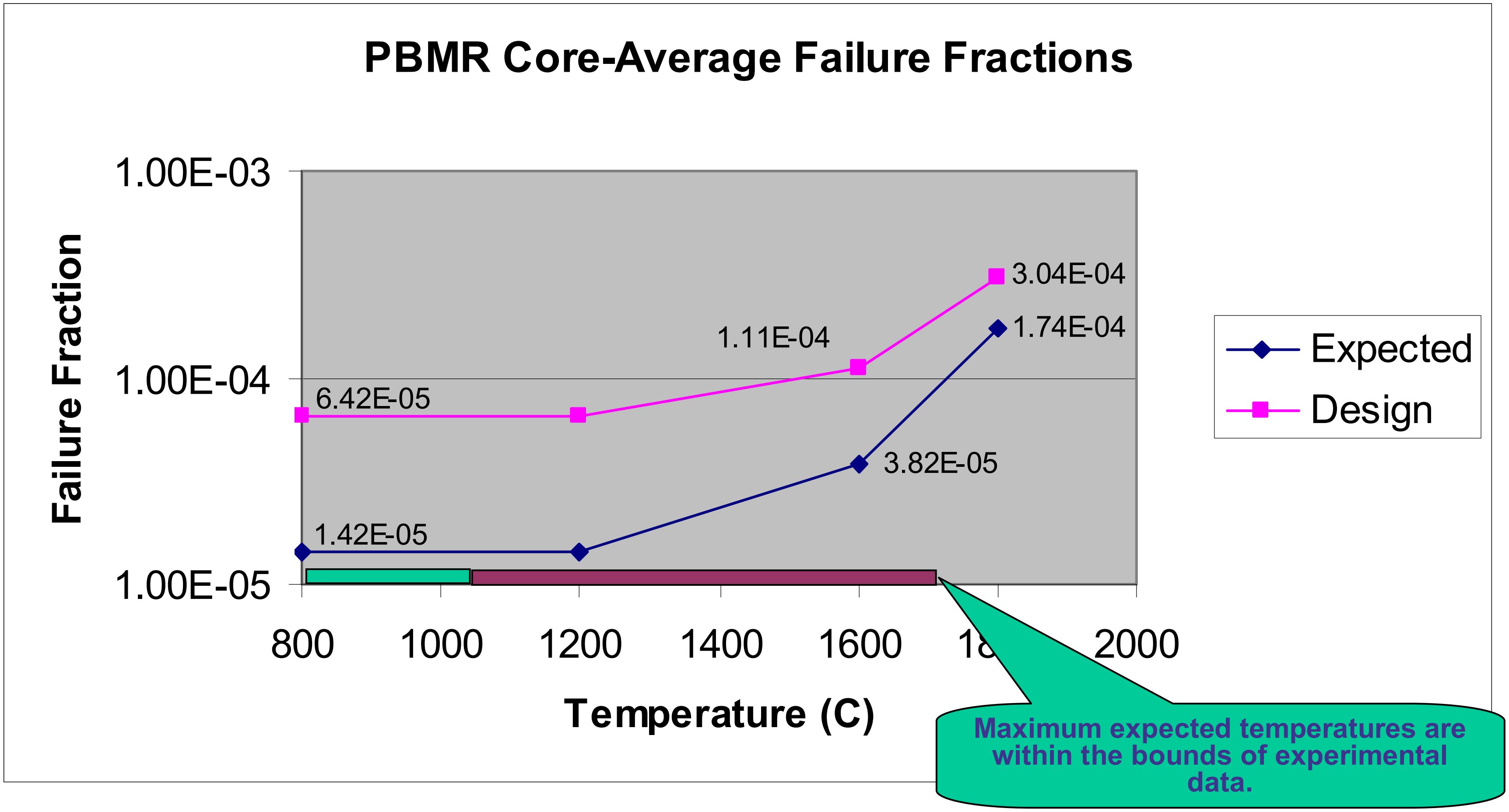
Example of Best-Estimate Fuel Temperature

Preliminary Results:
0.35% of spheres at temp of 1592ºC
6.3% of spheres at temps > 1500ºC



Best-estimate of maximum and average fuel sphere temperatures for a DLOFC with scram.

PBMR Core Average Failure Fractions



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Overview of PBMR Fuel Test Program

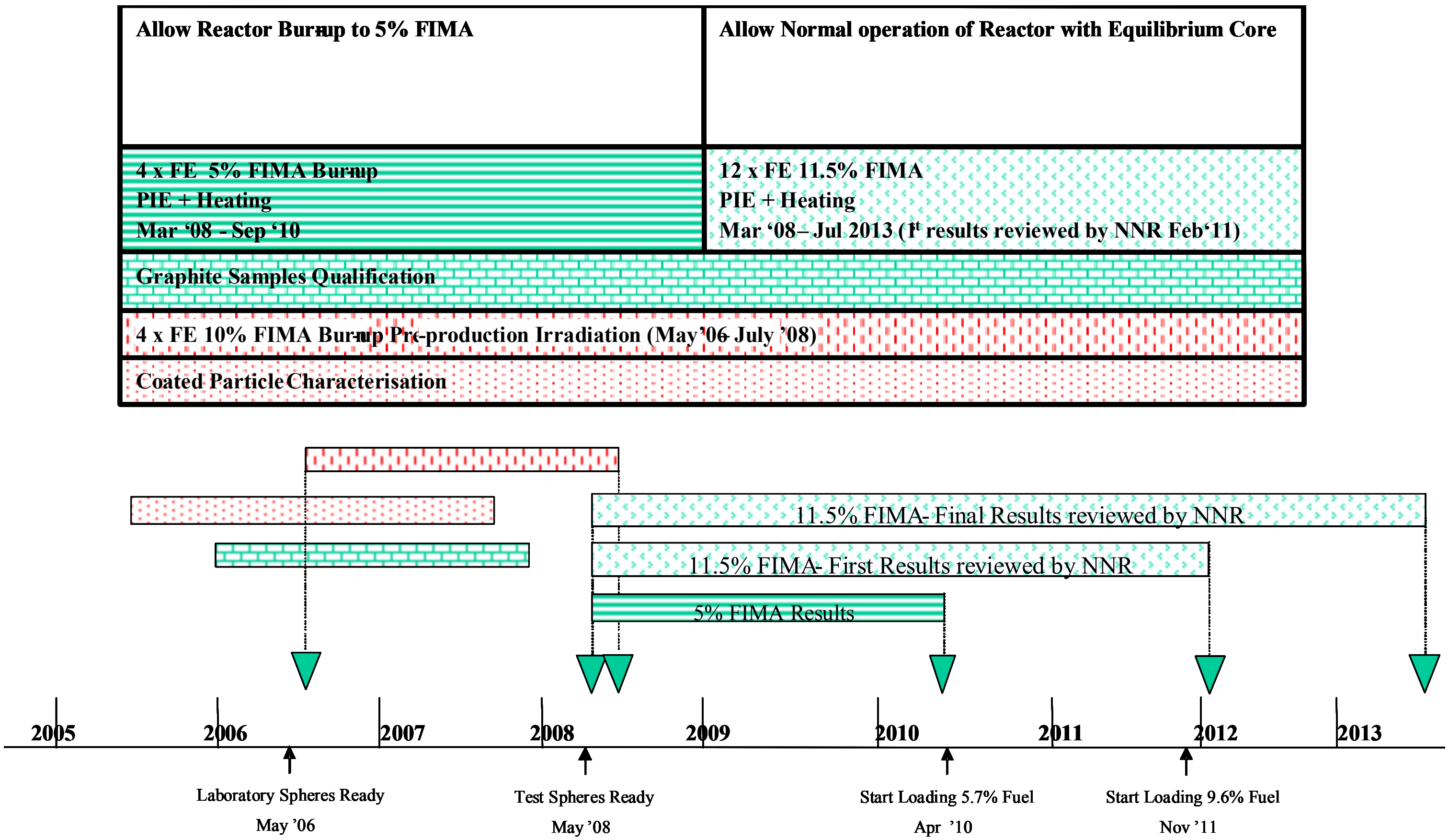
- **Basic Objectives:**
  - Support qualification of fuel for reactor startup
  - Support qualification of fuel for equilibrium operation
  - Support qualification of graphite materials
    - *Fuel sphere matrix material*
    - *Graphite block material*

Summary of Planned PBMR Tests

Test Run	Burn-up (% FIMA)	Temp. (ºC)	Post-Irradiation Heat-up Test	Objective
Support Plant Start-up • 4 spheres (~58,000 coated particles)	5	1200	3 FE to 1600ºC	Independent pre-characterization of fuel. Qualification to 5% FIMA. Zero or low numbers of coated particle failures indicate failure fractions ranging from $5x10^{-5}$ to $7x10^{-5}$ respectively
Support Equilibrium Operation • 12 spheres (~174,000 coated particles	11.3	900/1150	11 FE to 1600ºC	Full fuel proof test, including simulated PLOFC in test reactor. Detailed PIE.
Machined Graphite Qualification	-	High, Low, Average	None	Measurement of irradiation characteristics.
Pressed Graphite Qualification	-	High, Low, Average	None	Measurement of irradiation characteristics for fuel sphere graphite that cannot be measured on fuel containing spheres.

Values for FIMA may be revised.

PBMR Test Schedule Overview



Values for FIMA and enrichment are "nominal" and may be revised (e.g., initial enrichment may be less than 5.7%)

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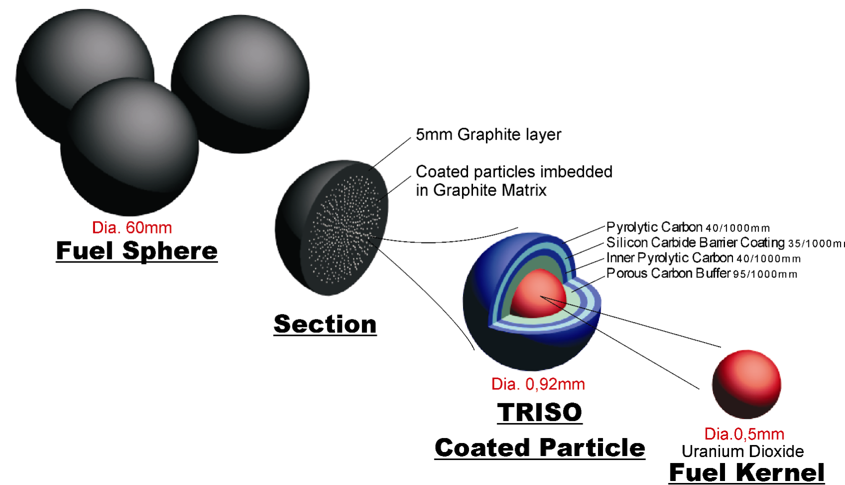
Inherent Design Features

- Safety is ensured by a combination of design features, operational limits, and coolant activity monitoring.

- First level of protection against fission product releases is the design (e.g., ceramic fuel particles, dimensions, densities) and its quality established via the manufacturing process and QC inspections.

Compliance with Performance Envelope

- **Design features which help control fuel temperature during plant operation:**
  - Fuel kernels: stoichoimetry, density, diameter and sphericity.
  - Coated particles: layer thickness, density, uniformity, uranium content and enrichment.
  - Coated particle batches: mixed to avoid grouping of faulty particles in fuel spheres.
  - Fuel spheres: diameter, uranium content, conductivity and strength of matrix material.



Monitoring and Control During Operation

- **Process parameter controls**
- **Fuel burn-up control**
  - Control of process parameters and discharge burn-up during normal-operation limits fuel temperatures such that radioactivity releases will be within regulatory limits
- **Coolant activity level**
  - Measurement system currently being designed

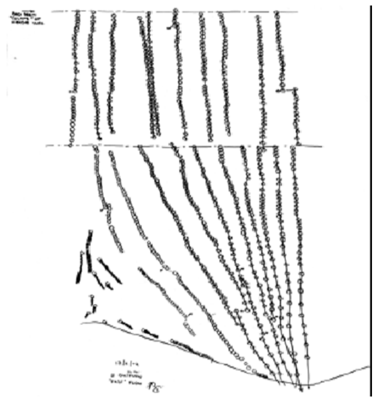
Plant Operational Controls

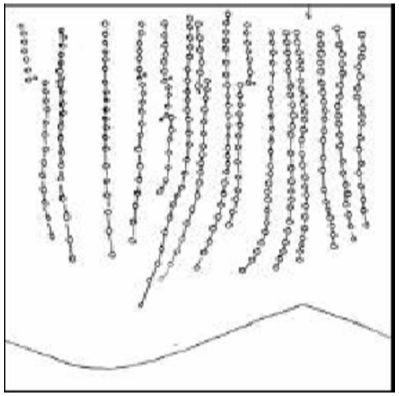
- **Main process controls related to fuel temperature**
  - Reactor inlet temperature
  - Reactor outlet temperature*
  - Helium inventory
    - *Flow rate via reactor delta-P**
  - System Pressure*
  - Reactor power
    - *Source range neutron flux**
    - *Power range neutron flux**
    - *Neutron flux period**
    - *Integrated power range neutron flux**

- *** Reactor Protection System input**

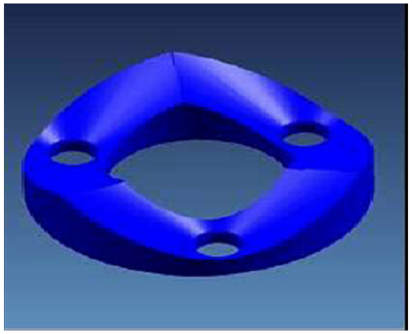
Fuel Burn-up Monitoring and Control

- **Burn-up of each sphere is measured after each pass through reactor**
  - 2 to ~40 seconds/measurement
    - *fuel vs. graphite sphere discrimination*
    - *"new" vs. used fuel discrimination – gross gamma*
    - *detailed gamma analysis*
- **Measurement based on concentration of CS-137**
  - Gamma emissions from daughter Ba-137m
- **Burn-up accuracy +/- 4%**





2 Outlet Core Base



3 Outlet Core Base

Coolant Radioactivity Monitoring

- **Fuel integrity is monitored during normal operation and AOOs by measurement of noble gas fission product levels in the coolant.**
  - Continuous gamma spectroscopic measurement
  - Remedial action taken if fuel failure fraction in the core indicates larger-than-expected increases

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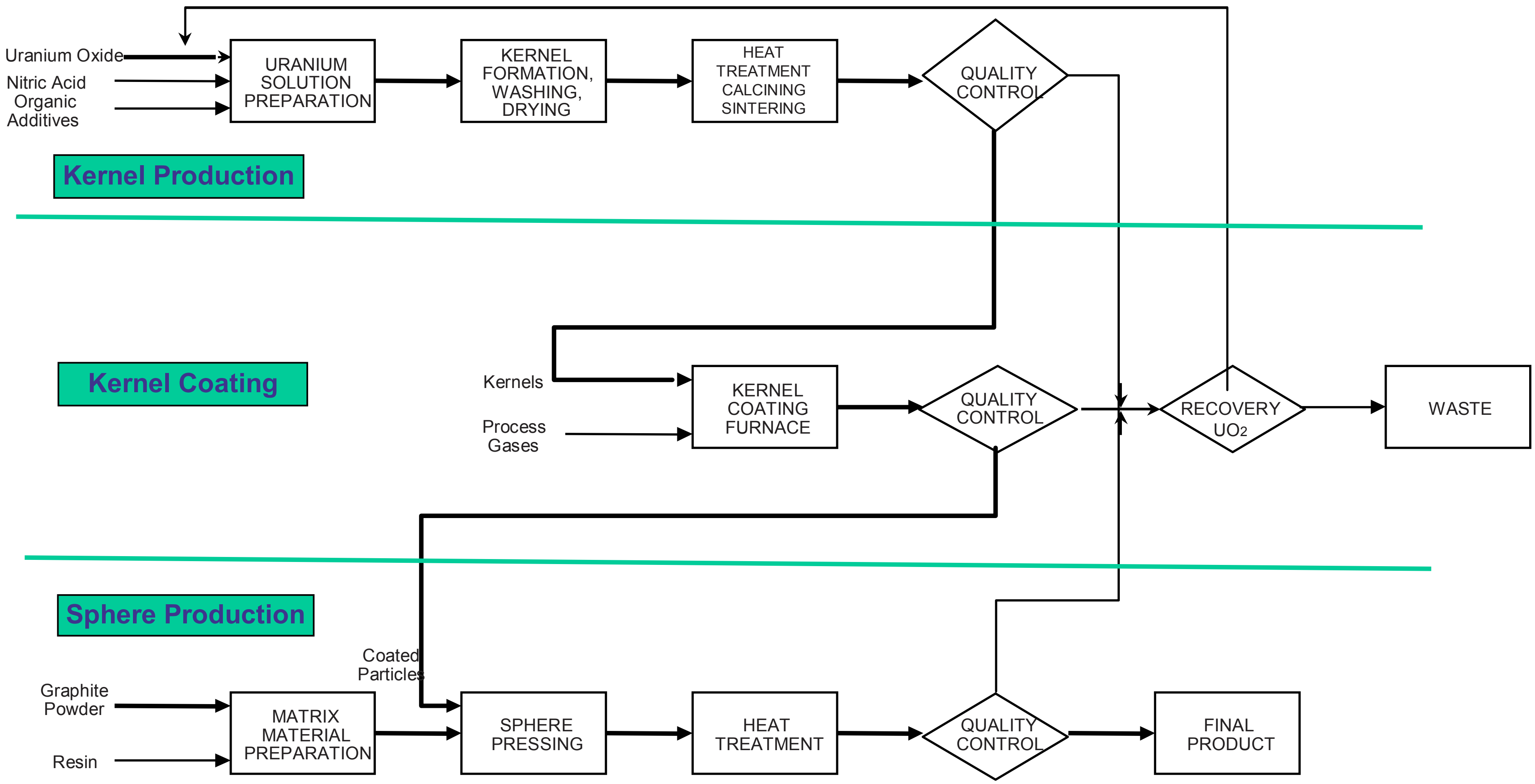
Fuel Manufacturing and Quality Controls

- **Equivalence of German & PBMR manufacturing processes**
  - Use the same fuel specification
  - Use the same process steps
  - Apply QC to same parameters
  - Use equivalent materials (that comply with similar specifications)
  - NUKEM (the original German manufacturer) is providing consultation on the fuel specification, manufacturing process, pilot plant design, etc.

Fuel Manufacturing Process - Overview



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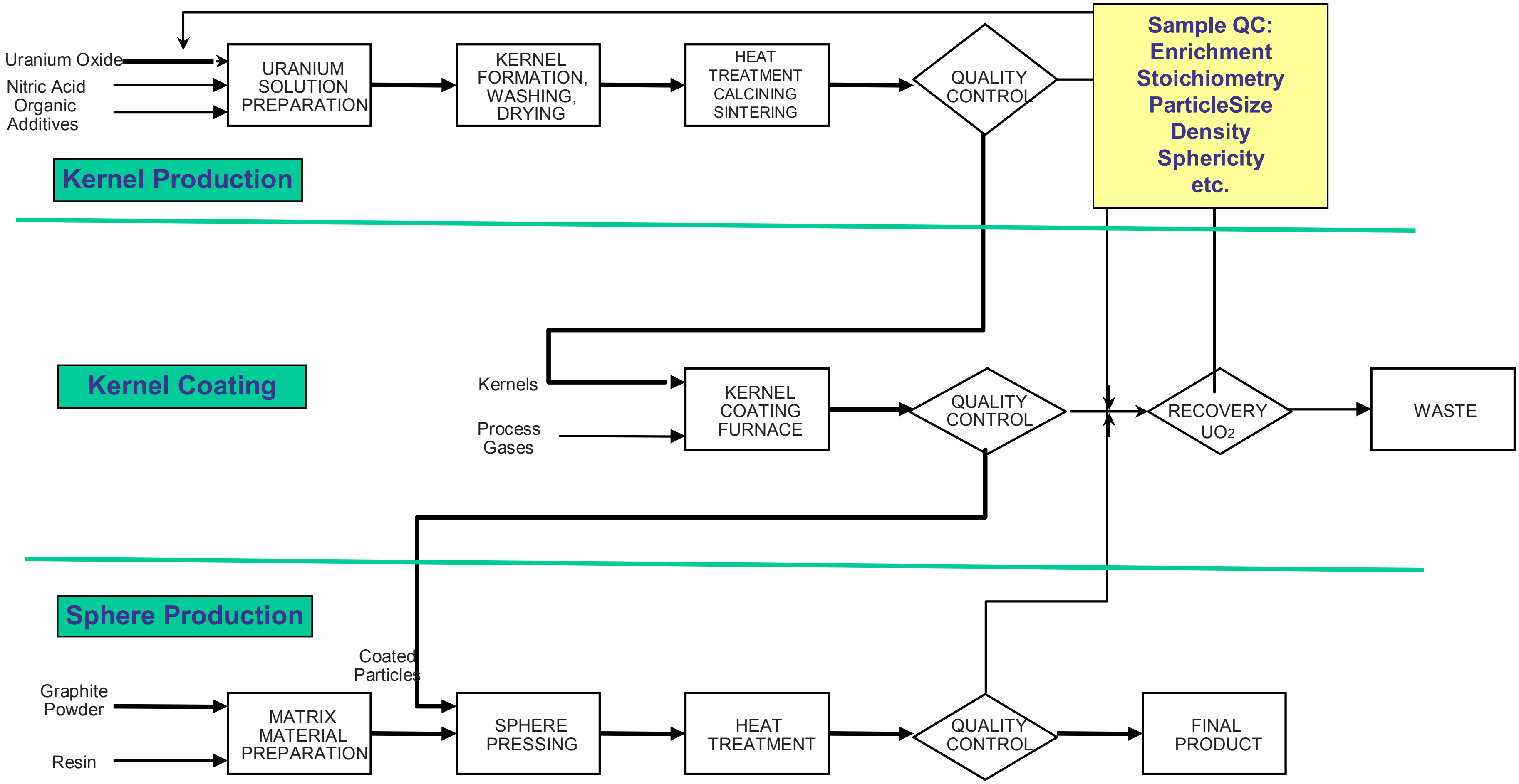
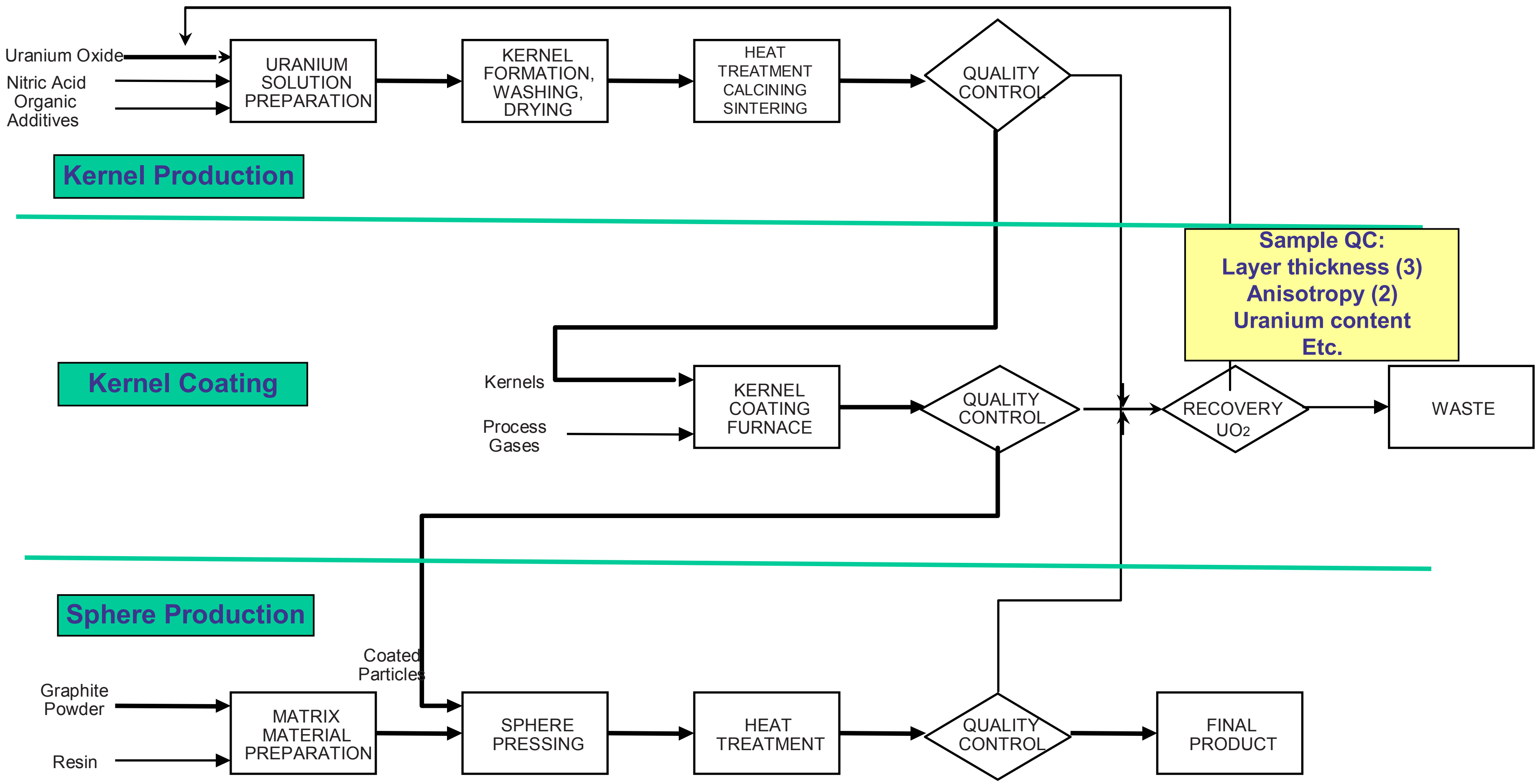
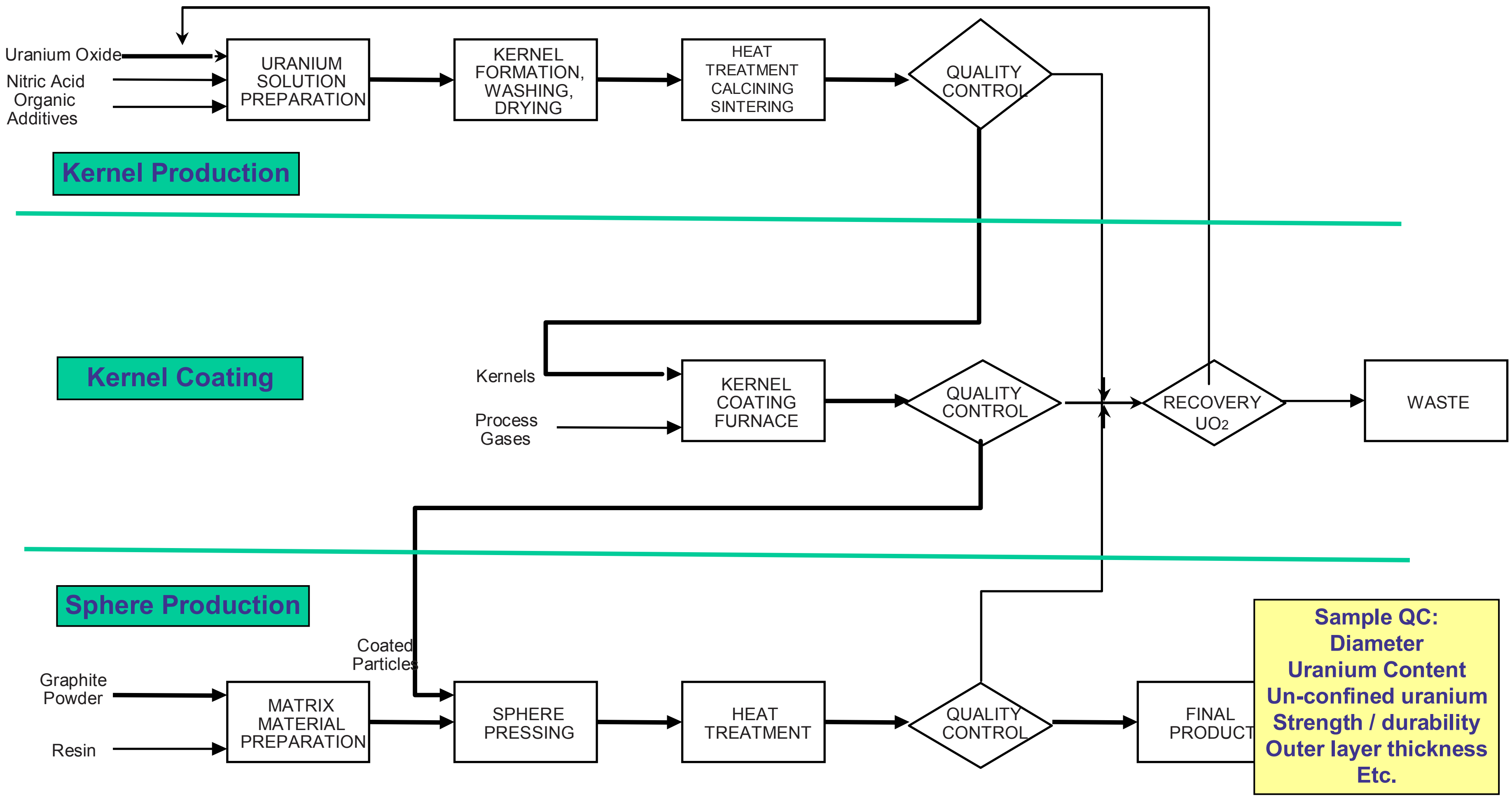


Fuel Manufacturing Process - Overview



Fuel Manufacturing Process - Overview



Manufacturing Process Documentation

- **Issues to be addressed with NRC staff**
  - Process description
  - Certified design features and ITAAC

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Exelon RAIs

Area of Review	Timing	Pre-application Work Item(s)
PBMR Nuclear Fuel		
RAIs 8.1.1-8.1.23	1	
RAIs 8.2.1-8.2.12	2	
Fuel Fabrication Quality Control Measures and Performance Monitoring		
RAIs 9.1.1-9.1.12	1	
RAIs 9.2.1-9.2.10	2	
PBMR Fuel Qualification Test Program		
RAIs 10.1.1-10.1.34	1	
RAIs 10.2.1-10.2.12, 10.2.14-10.2.23, 10.2.28b, 10,2,29, 10.2.31, 10.2.32	2	
RAIs 10.2.13*, 10.2.24*-10.2.28a*, 10.2.30*	2	

Exelon RAIs

Area of Review	Timing	Pre-application Work Item(s)
High Temperature Materials, Graphite		
RAI 1.2.24	**2**	
Analytical Codes and Software Control		
Panama		
RAIs 5.1.1-5.1.5	**1**	
Fresco		
RAIs 5.1.6, 5.1.7	**1**	
Panama and Fresco		
RAIs 5.1.8, 5.1.9	**1**	

Exelon RAIs

Area of Review	Timing	Pre-application Work Item(s)
Core Design and Heat Removal		
RAIs 6.1.1, 6.1.2	1	
RAI 6.2.1*, 6.2.5*-6.2.14*, 6.2.24*-6.2.35*, 6.2.37*, 6.2.38*, 6.2.44*, 6.2.48*, 6.2.49*, 6.2.54*	2	

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Proposed Pre-application "White Papers"

- **Proposal: One white paper for each focus issue**
  - PBMR irradiation test program and performance envelope
  - PBMR operating controls and monitoring limits
  - PBMR fuel manufacturing process and production controls

Pre-application Milestones

Document	Submittal	NRC Review	PBMR Response	Meeting	NRC Review Summary
PBMR irradiation test program and performance envelope					
PBMR operating controls and monitoring limits					
PBMR fuel manufacturing process and production controls					